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FIELD-EMITTER ARRAYS FOR RF VACUUM MICROELECTRONICS

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SRI Project 2743

Prepared for:

Defense Advanced Research Projects Agency
Defense Sciences Office
Virginia Square Plaza
3701 North Fairfax Drive
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Attn: Dr. Bertram H. Hui

ARPA Order No. 8162

Contract MDA 972-91-C-0029

Covering the Period: 1 January through 31 March 1992

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SRI International has completed the second quarter of a program to develop field-emitter arrays for vacuum microelectronics. The goals of the effort are 5mA total current at 5 A/cm2 for at least 1 hour, and demonstrated modulation of the emission at 1 GHz.

Improved vendor deposition of the oxide layer indicated that a cathode achieving 1000 A/cm2 shows very brittle oxide that tends to break up and flake off under the pressure of the contact leads. Low-capacitance cathode fabrication studies were temporarily discontinued after equipment failure.

To date, 1000-tip cathodes have been operated with carefully processed, closed-spaced nickel anodes, presently at 15 mA and 22.8 A/cm2, for over 2700 hours.

Major effort was directed toward detailed design of the apparatus required for microwave measurements, and on developing technologies for assembling microstrip lines and lead bonding them to SMA coaxial connectors and cathode arrays.

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EXECUTIVE SUMMARY

SRI International has completed the second quarter of Phase I of a research and development program on the SRI Spindt-type field-emitter-array cathode with a view toward eventual applications in microwave amplifiers. Goals for this first phase have been set at 5 mA total emission, with a current density of 5 A/cm^2 for at least 1 hour and demonstrated modulation of the emission current at a frequency of 1 GHz. Our approach has been to identify methods of adapting and modifying the basic cathode structure for microwave operation and to experimentally investigate means of implementing those methods.

During the quarter we have accomplished the following, as documented in detail in this technical report, which encompasses information delivered earlier to the NRL:

- Continued research on basic cathode technology as defined by the goals of the DARPA program and related NRL project (Section 1)
- Confirmed improved vendor deposition of the oxide layer for our low-capacitance fabrication studies (Section 2)
- Conducted emission tests on sets of 1000-tip cathodes, with both close-spaced nickel plate anodes and stainless steel tube-shaped anodes (Section 3)
- Nearly completed detailed design work, so that fabrication of the apparatus required for microwave measurements can begin soon (Section 4)
- Planned activities for the period of 1 April through 30 June (Section 5)

CONTENTS

1. INTRODUCTION

SRI International is participating in an effort of the Defense Advanced Research Projects Agency (DARPA) and the Naval Research Laboratory (NRL) to perform research and development on the SRI Spindt-type field-emitter-array cathode for eventual microwave amplifier applications. The current DARPA program is the vehicle for advancing the basic cathode technology for microwave applications (e.g., reducing intrinsic capacitance and driving voltage requirements), and continues the original program plan to establish the characteristics of the cathode in its preprogram state of development, identify methods of adapting and modifying the structure for microwave operation, and experimentally investigate means of implementing those methods. For the NRL program, which began earlier than the DARPA project, SRI has shifted emphasis to the support of NRL's in-house vacuum microelectronics program by providing NRL with state-of-the-art Spindt-type cathodes and consultation on setting up and using cathodes.

Our cathode fabrication development was delayed by equipment failure (the turbopump on our primary coating system). At the end of the period, a replacement had been located, and installation was started. Because of this, work was largely devoted to the detailed design of the microwave apparatus needed for high-frequency tests. This will be completed early in the next period, and fabrication will begin. We plan to have the apparatus ready for test at the end of the next period.

At the beginning of the program, two areas of development required immediate attention. The first was a materials and processing issue related to providing and maintaining a suitable vacuum environment for the cathodes. The second related to the cathode's inherent high capacitance and means for reducing that capacitance to a level that is consistent with the microwave applications envisioned for the cathode.

Our approach has been to research these two issues in parallel, using an easy-to-build, low-frequency-triode configuration fabricated on a TO-5 header as a test vehicle for materials and processing studies, and at the same time designing and researching fabrication techniques for building high-frequency-cathode structures on dielectric substrates (e.g., quartz or glass). Specific tasks that are being addressed on these related programs are:

1. Fabrication of a supply of state-of-the-art cathodes for use in establishing cathode characteristics, and for developing structures, circuits, and procedures for testing the cathodes as triodes.

2. Development of a close-spaced anode test configuration that can be used to investigate triode characteristics at low frequency (kHz to MHz) in order to study the known problems with cathode survival under close-spaced anode conditions.

3. Development of a circuit for driving the cathodes and demonstrating gain, frequency response, and peak emission levels.

4. Studies of advanced cathode structures (geometry, fabrication technology, and processing) for high-frequency operation.
5. Investigations (with NRL) of cathode mounting and connecting procedures using practices that are consistent with the microwave goals of the effort.
6. Consultations with the NRL staff on the experimental results and applications of the cathode technology.

2. LOW-CAPACITANCE CATHODE FABRICATION

Low-capacitance cathode structures were designed and fabricated on the DARPA program, and samples without cones have been delivered to NRL for use in designing mounting structures and contact probes for NRL's in-house testing. As soon as the fabrication technology is developed on the DARPA program, sample working cathodes—for use in establishing NRL in-house experience and evaluation capability for experimental microwave field-emission devices—will be fabricated and delivered on the NRL program.

Since last quarter, the vendor has significantly improved the deposition of the oxide layer. However, postoperative inspection of the cathode that achieved 1000 A/cm^2 showed that the oxide is still very brittle and tends to break up and flake off under the pressure of the contact leads. As a result, we must do some additional work on the oxide deposition process before we have suitable operating samples.

An additional delay is due to the lead time on delivery of a pump for the vacuum coater we use for the gate film deposition on 5-inch wafers. The turbo pump failed in early December, and we do not yet have a replacement. This has caused a major setback to our schedule, because the stepper available to us accepts only 5-inch-diameter wafers. We can continue with some of the basic cathode studies on silicon using cathode samples with holes patterned in them from earlier work. However, no new work on low-capacitance structures can be done until the new pump is installed and operating.

3. CATHODE EMISSION TESTS

In the previous quarterly report, emission tests with two sets of three 1000-tip cathodes were reported. One set was under test with stainless steel tube-shaped anodes, and one set was set up with close-spaced (≈1 mm) nickel plate anodes. As reported previously, two of three cathodes with the tube-type anodes had stabilized at 10 mA emission but developed gate-to-base leakage because of overheating of the anodes and cathodes during a period of operation at 20 mA. The third (53i-300-8S) failed because of excessive base-to-gate leakage. As of 10 January, the two remaining cathodes (53i-300-8Q and 53i-300-8T) have continued to operate at 10 mA, but have required higher voltages (by ≈10%) since a weekend shutdown due to a power failure at SRI. (The higher voltage was probably required by a change in the vacuum environment while the ion pump stopped operating for 2 days.) The base-to-gate leakage continued to increase (200 μA and climbing) with time on both cathodes, and it appeared that they were destined to fail because of excessive leakage, just as the first cathode had. Therefore, they were shut down and replaced with new cathodes on 13 January. Figure 1 shows the current-versus-voltage curves for the two cathodes at shutdown, when total operating time was 1850 hours.

The stainless steel tube-type anodes in this test chamber will be replaced with nickel anodes and tested to see if the leakage was due to deposition on the cathodes from the anodes when they were overheated during operation at 20 mA.

The cathodes in the system with the close-spaced nickel plate anodes have been operating since 1 August 1991. One of these cathodes (53i+300-7R) also failed to a short circuit prior to the power shutdown. The other two (53i+300-7P and 53i+300-7Q) have been operating at 10 mA peak emission or higher with 180 V on the anode continuously since 5 September 1991 (except for the power outage). They were also taken to 20 mA peak emission for a short time and, as with the tube-type anodes, excessive heat caused a problem. In this case, the foil making contact with the gate film pulled away from the gate and lost contact because of the thermal expansion. Contact was reestablished by lowering the temperature of the structure. These cathodes are presently operating at 15 mA peak (15 μA/tip) with our standard 60-Hz half-wave rectified driving voltage, and have been at that level since 12 November 1991 (≈2700 hours and counting). During that time, the cathodes have slowly become more and more alike in their performance. Figure 2 shows the current-versus-voltage characteristics of these two cathodes. The cathodes are 1000-tip arrays covering an area of 256 μm by 256 μm so that the peak current density is 22.8 A/cm^2. It is noteworthy that this performance easily meets the related DARPA program's requirements of 5 mA and 5 A/cm^2 for 1 hour.

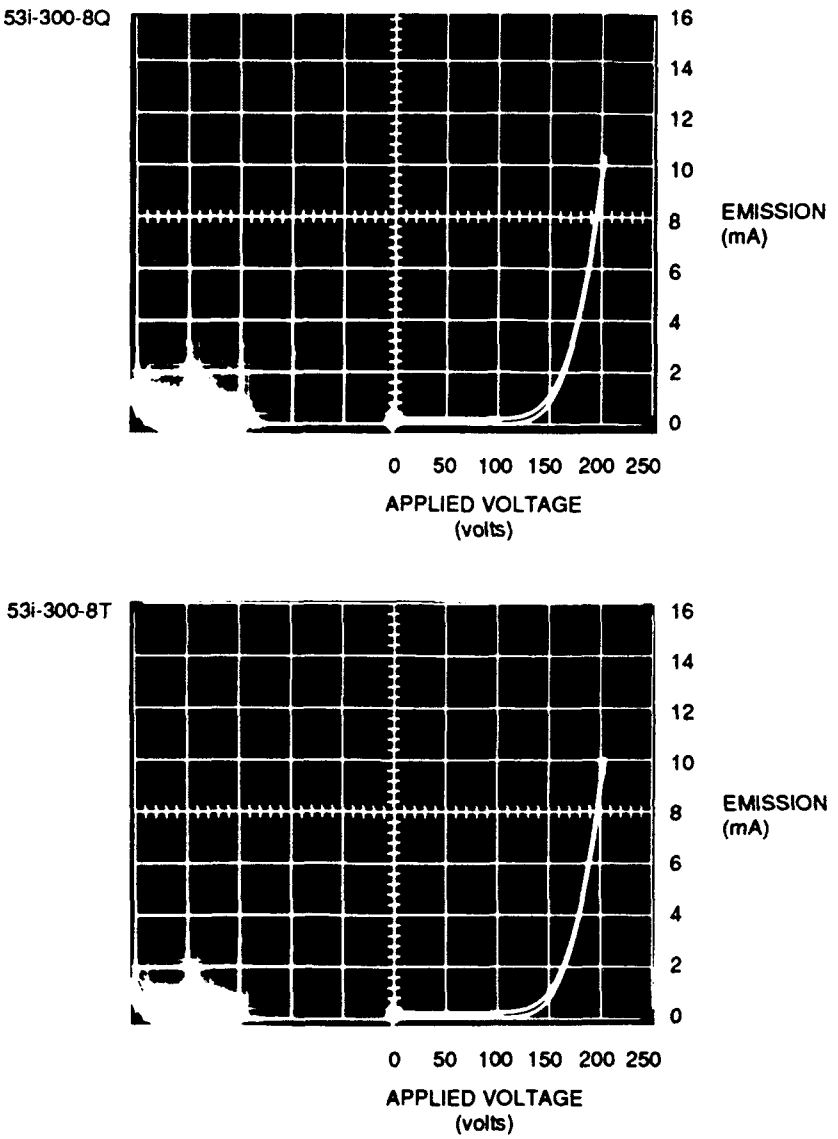

Figure 1. Current/voltage curves for cathodes 53i-300-8Q and 53i-300-8T at the time of shutdown after 1850 hours of operation

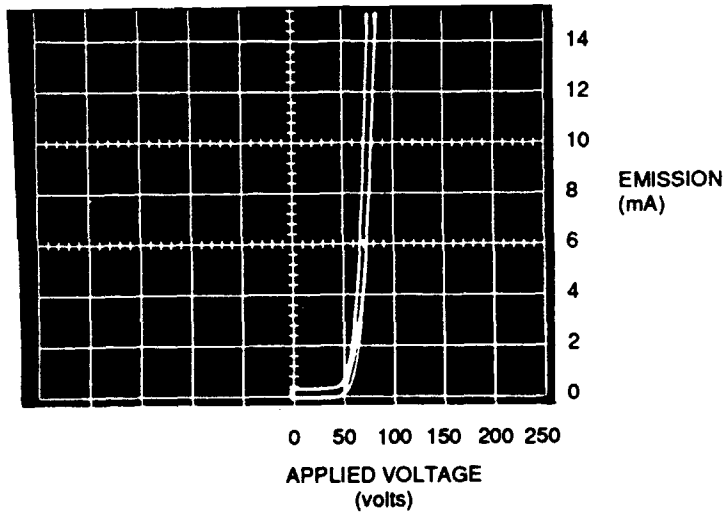

Figure 2. Current/voltage curves for cathodes 53i-300-7P (low voltage) and 53i-300-7Q (higher voltage) with close-spaced nickel plate anodes

4. MICROWAVE MEASUREMENTS

The bulk of the effort has been on the detailed design of the apparatus required for testing cathode arrays at microwave frequencies, and on developing technologies as needed for assembling microstrip lines and lead bonding them to the SMA coaxial connectors and the cathode arrays. Completion of the design and start of construction are expected to occur early in the next quarter.

5. WORK PLANNED

The main focus of our effort during the next period will be to bring our box coater back on line, and to bring two new pieces of apparatus—a CVD/RIE system and an in-line four-target sputtering system—on line. When these tools are fully operational, they will be applied to advanced low-capacitance cathode fabrication. We will begin fabrication of cathodes in this configuration as soon as possible, so that studies of high-frequency modulation of the emitted beam can be set up at NRL.

We will also begin fabrication of the microwave measurements apparatus.